

# Analysis of Strain Gage Reliability in F-100 Jet Engine Testing at NASA Lewis Research Center

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ANALYSIS OF STRAIN GAGE RELIABILITY IN F-100 JET ENGINE TESTING  
AT NASA LEWIS RESEARCH CENTER

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SUMMARY

A reliability analysis was performed on 64 strain gage systems mounted on the 3 rotor stages of the fan of a YF-100 engine.

The strain gages were used in a 65 hour fan flutter research program which included about 5 hours of blade flutter. The analysis was part of a reliability improvement program. Eighty-four percent of the strain gages survived the test and performed satisfactorily. A post-test analysis determined most failure causes. Five failures were caused by open circuits, three failed gages showed elevated circuit resistance, and one gage circuit was grounded. One failure was undetermined.

INTRODUCTION

The most commonly used instrument for the measurement of stress levels and associated vibration or flutter frequencies of rotating compressor blades during engine test programs is the electric resistance strain gage. The strain gages are mounted directly on the blades at points chosen to give information on vibratory stress characteristics. Lead wires are attached to the strain gage and routed down the blade to the root. Then a jump is made from the blade to the disk in such a way as to allow for the relative motion between the blade and the disk. The lead wires then proceed from the disk, along the shaft to a slip-ring system, and to the recording and monitoring instrumentation in the dynamic data monitoring room.

This strain-gage system must survive in an environment consisting of rotating machinery generating high g-loads, a high-temperature, high-velocity gas stream with entrained erosive particles, and a wide variety of stress levels caused by complex vibratory modes. NASA, the Air Force, and some aircraft engine companies have been involved in a continuing effort to improve strain-gage reliability.

Following a series of fan blade flutter tests on YF-100 engines with high gage failure rates, a carefully documented and controlled program on the next YF-100 fan blade flutter test was instituted to investigate the problem. The results were reported in reference 1. Several common failure modes were identified in this test, and recommendations were made to correct the problems. This investigation was followed by a contract effort to determine the state-of-the-art of strain gage systems for jet engine testing. Several different strain gage system designs were tested in this program. The gages were again mounted on a YF-100 fan, but the tests did not include flutter. The results were reported in reference 2.

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The results of these two investigations were used to determine the strain gage system design to be used on the next test of a YF-100 engine in the fan blade flutter research program. This report presents the analysis of strain gage reliability in that test.

## BACKGROUND

Several conclusions and recommendations resulted from the failure analysis of reference 1. In that program, epoxy-cemented and flame-sprayed strain gage installations were investigated. The primary failure mode for epoxy-cemented gages was erosion of the cement, but only on the pressure side of the blade. The primary source of erosive particles in ground-test facilities is corrosion of test facility piping.

For flame-sprayed installations, erosion was not a serious problem for tests lasting up to 50 hours. Primary failure mode was elevated resistance of the gage grid, caused by the high strain levels of flutter testing. Increased gage resistance has been correlated with progressive deterioration of a strain gage on a microscopic level, leading to failure (loss of electrical signal) with resistance increases of only about 10%. It was thought that a hardening agent added to the flame-sprayed material may have contributed to this problem. Since erosion was not a problem in flame-sprayed installations, use of the hardening agent could be eliminated in future tests.

The variables investigated in reference 2 included blade-to-disk jumps, gage wires, lead wires, and materials of fabrication. Primary failure mode was at the blade-to-disk jump wire for both bare and insulated lead wire. It was determined that, by using great care in applying the cementing material evenly and uniformly around these jumps, this failure mode could be controlled.

The evaluation of fabrication materials included epoxy cement, flame-sprayed aluminum oxide powder, flame-sprayed Rokide rod, and ceramic cements. The previous conclusions regarding erosive properties of epoxy cements and ceramic materials was verified. Although small differences in erosive properties among the ceramic materials was observed, all were acceptable and presented no erosion failure problems. Two types of gage materials, Nichrome V and platinum/8% tungsten, were used with success.

Gage grid resistance increase was not a problem. A hardening agent had not been used in this test on the ceramic materials, and it was felt that this had contributed to the reduction of gage grid resistance increase failures. However, blade stress levels had not been as severe as previous tests because this was not a flutter test. So the reduction in failures due to increased gage resistance was not completely conclusive.

## DESCRIPTION OF TESTS AND INSTRUMENTATION

A fan blade flutter test was conducted at Lewis Research Center as part of the Full Scale Engine Research Program, using YF-100 engine hardware. Total engine test time was 65.8 hours, divided into 18 test runs. Approximately 5 hours of this time was spent in flutter conditions, with a total of 110 flutter points. Twelve stall points were included in the test. A slip ring

failed in the 31st hour of testing and was replaced. The engine was operated at inlet temperatures up to 572° C (300° F).

Eighty-six (86) strain gages were mounted on the 3 rotor stages of the fan in the pattern shown in figure 1. Forty-six of these gages were monitored during engine testing and are indicated in figure 1 with shading. The remainder were available as spares but were not needed. Front and top views of the blade (fig. 1(a)) show the exact gage location positions. All gages were installed using a composite process consisting of a ceramic flame-sprayed base-coat and overcoat and a ceramic cement coating over the gage. Table I lists the materials used in the fabrication of the strain gage systems. General fabrication and application techniques are discussed in references 2 and 3.

Following the engine test, a post-test analysis of some of the strain gage systems was performed. Only gages mounted on the first stage blades were available for a complete analysis. All 50 of these gages, both monitored (32) and unmonitored (18), were included. The analysis consisted of the following:

- (1) Gage circuit continuity was checked;
- (2) Resistance was measured at several points along the gage circuit, including measurements on the airfoil at the gage grid. These were compared to resistance measurements made at other times during the test program;
- (3) Measurement was made of installation thickness along the gage path on the airfoil to determine erosion patterns;
- (4) Failure modes were determined using this information.

In addition, resistance measurement data was available for the 14 second and third stage gages monitored during the test. These measurements were made at the slip ring during and after testing, and this information was useful in determining failure mechanisms. Thus, a total of 64 gages were subjected to complete or partial post-test failure analysis.

Figures 2 to 4 are photographs taken of the fan after disassembly from the engine. Figure 2 presents a view of the entire first stage rotor. The strain-gaged blades can be seen to be arranged in 4 groups of 4 blades each. In figure 3, gage installations can be seen on the convex (suction) side of the blades. A closeup of the blade-to-disk jumps is shown in figure 4. The Chromel-Alumel 28 gage duplex wire can be seen embedded in epoxy cement. Only the first stage gages could be encapsulated in this manner because of the temperature limitation on the epoxy cement. On the second and third stages the blade-to-disk jumps were made with the same wire but were not encapsulated.

#### FAILURE ANALYSIS

Table II tabulates the information in figure 1, showing the gages that were included in the failure analysis, and lists the failures by location. Failure rates for the first, second, and third stage gages were 10%, 50%, and 17%, respectively. The high second stage failure rate is not considered statistically significant because of the small sample size and because the failures were distributed randomly in time.

This can be seen in the Strain Gage Failure Log (table III), which identifies the failed strain gages, lists their location, and specifies the time of failure, where available.

Figure 5 presents failure rate in graphical form. Failure rate curves of previous tests are included for comparison. Flutter tests 1 to 3 preceded the tests of references 1 and 2. Progress is seen to be quite significant during the reliability improvement program. These improvements were achieved even though time in flutter increased dramatically and blade stresses were at least as severe in the present test.

The failure modes are shown in table IV. Three of the five open circuit failures were traceable to the gage grid. The exact location of the other two open circuits could not be isolated due to inaccessibility of the second and third stage blades to complete post-test analysis.

Increasing gage resistance has been correlated with progressive deterioration of a strain gage (ref. 1). Only one failure was attributed to this failure mode. In two other circuits showing high resistance, the exact location could not be determined due to inaccessibility. The cause of one gage failure could not be determined.

Insulation thickness measurements on first stage strain gage systems showed no significant erosion problems. No failures were attributable to this failure mode.

There were no jump failures on stage 1, which is the only stage accessible to direct measurement. It was on this stage that the jumps were embedded in epoxy cement. It appears that this technique provided the jump with sufficient flexibility to allow for the relative movement between blade and disk, while at the same time it afforded greater protection than unencapsulated jumps.

#### CONCLUDING REMARKS

A reliability analysis was performed on 64 strain gages mounted on first, second, and third stage rotors of the fan of a YF-100 engine. Gages were installed using flame-sprayed ceramics. The engine was tested for 65 hours including about 5 hours in flutter conditions, as part of a fan flutter research program. Despite the severe test conditions, only 10 gages (16%) failed. A failure analysis was performed, and the following conclusions were determined:

1. Three gages failed due to open circuits at the gage grid. Two other open circuit failures occurred, but due to inaccessibility, the location could not be determined.
2. One gage failed due to high resistance at the gage grid. Two other circuits showed high resistance, but due to inaccessibility, the location could not be determined.

3. One gage had a grounded circuit, but its location could not be determined.
4. One cause of failure was not determined.
5. Erosion was negligible on these flame-sprayed installations.

#### REFERENCES

1. Holanda, Raymond, and Krause, Lloyd N.: Reliability Analysis of 45 Strain-Gage Systems Mounted on the First Stage of a YF-100 Engine. NASA TM-73724, Sept. 1977.
2. Dolleris, G. W., Mazur, H.J., and Kokoszka, Jr., E.: Strain Gage System Evaluation Program Final Report. NASA CR-159486, March 1979.
3. Weise, R. A., and Foster, J. H.: High Temperature Strain Gage System for Application to Turbine Engine Components. AFWAL-TR-80-2126, Jan. 1981.

TABLE I. - MATERIALS USED IN STRAIN GAGE INSTALLATIONS

- o Precoat - Metco 443
- o Basecoat - Rokide H
- o Gage installation cement - GA-100
- o Overcoat - Rokide H
- o Gage grid - 0.0009" dia. 92% Platinum - 8% Tungsten for gages on airfoil surfaces.
- o Gage grid - 0.0006" dia. 92% Platinum - 8% Tungsten for gages on blade shrouds.
- o Gage leadwires - 0.005" dia. 90% Platinum - 10% nickel attached along a convoluted path.

Blade to disk "jumps" and disk leadwires - 28 gage Chromel/Alumel solid conductors, with asbestos primary insulation and fiberglass outer insulation. This wire was held in place with titanium tack straps combined with GA-100 cement.

TABLE II. - SUMMARY OF STRAIN GAGE FAILURES BY FAN STAGE LOCATION

Fan stage	Total gages mounted on stage	Gages monitored during test	Gages in failure analysis	Failures
1	50	32	50	5
2	20	8	8	4
3	<u>16</u>	<u>6</u>	<u>6</u>	<u>1</u>
TOTALS	86	46	64	10

TABLE III. - STRAIN GAGE FAILURE LOG

Rotor stage	Gage number	Gage location	Time of failure, hr
1	24	ASTE <sup>a</sup>	<1
1	22	ASTE <sup>a</sup>	<1
2	7	Tip	2.5
2	1	Tip	39.5
3	9	ASMT <sup>b</sup>	39.5
2	11	ASMT <sup>b</sup>	43
2	2	Tip	61
1	4	Tip	61
1	41	FSMT <sup>c</sup>	(d)
1	45	Shroud	(d)

<sup>a</sup>ASTE = Above shroud, trailing edge.

<sup>b</sup>ASMT = Above shroud, maximum thickness.

<sup>c</sup>FSMT = Front of shroud, maximum thickness.

<sup>d</sup>Not available.

TABLE IV. - SUMMARY OF FAILURE ANALYSIS<sup>a</sup>

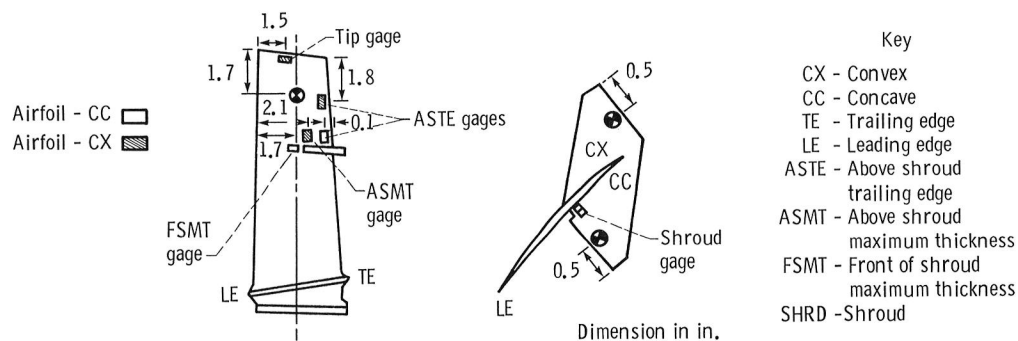
Type of failure	Number of failures
Open circuit	5
Grounded circuit	1
Increased resistance	3
Undetermined	<u>1</u>
Total failures	10

<sup>a</sup>Based on complete post-test analysis of 50 first stage gages and partial analysis of 14 second- and third-stage gages.



Slot no.	1	2	3	4	11	12	13	14	19	20	21	22	30	31	32	33
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Gage Location	Strain gage number																												Total
LE TIP-CX	1	2			3	4			5	6			7	8															8
TE TIP-CX	9	10							11	12																			4
ASTE-CC	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28													16
ASMT-CX			29	30			31	32			33	34			35	36													8
FSMT-CC			37	38				39			40	41				42													6
SHRD-CC	43	44			45	46			47	48			49	50															8
																													50



(a) First stage rotor.

Slot no.	1	2	16	17	31	32	46	47
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Gage Location	Strain gage number								Total
TIP	1	2	3	4	5	6	7	8	8
ASMT	9					10	11	12	4
ASTE		13	14	15	16				4
SHRD-CC	17					18	19	20	4
									20

(Note: Shading in table indicates gages monitored during engine testing.)

(b) Second stage rotor.

Slot no.	1	2	11	21	22	31
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Gage Location	Strain gage number						Total
TIP	1	2	3	4	5	6	6
ASMT	7	8	9	10	11	12	6
SHRD-CC	13	14		15	16		4
							16

(c) Third stage rotor.

Figure 1. - Strain gage location map.

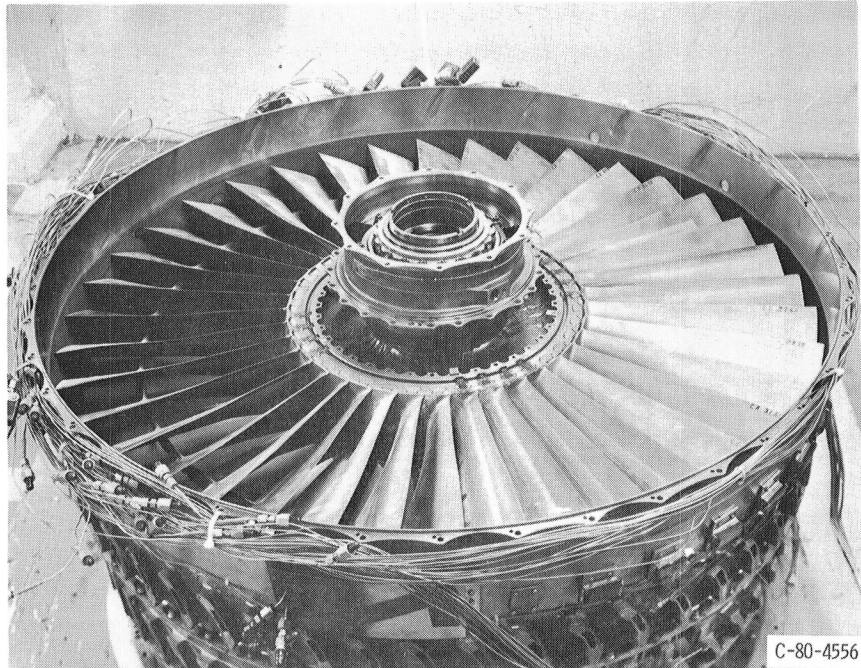


Figure 2. - Instrumented YF-100 engine fan.

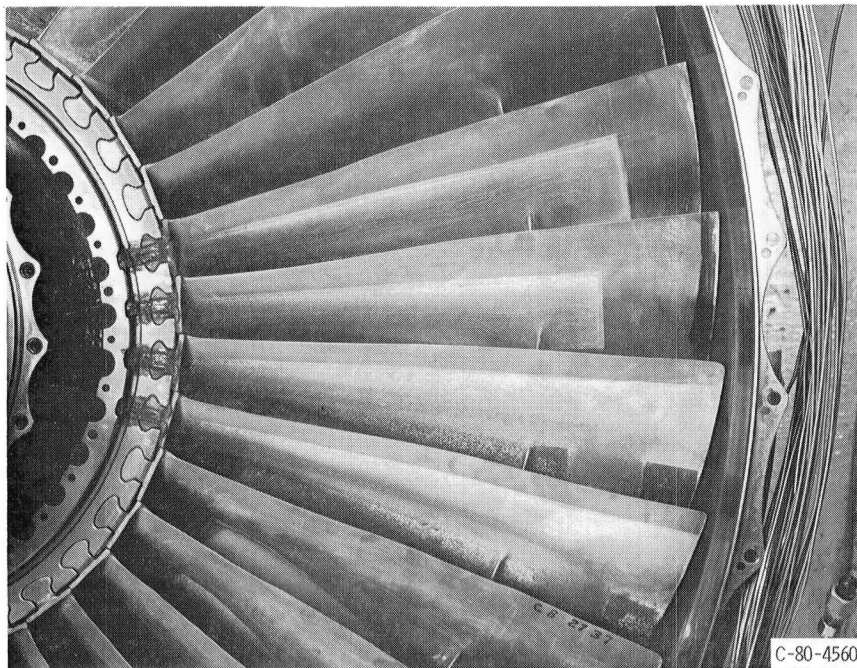


Figure 3. - Strain gage installations on first stage of YF-100 engine fan.

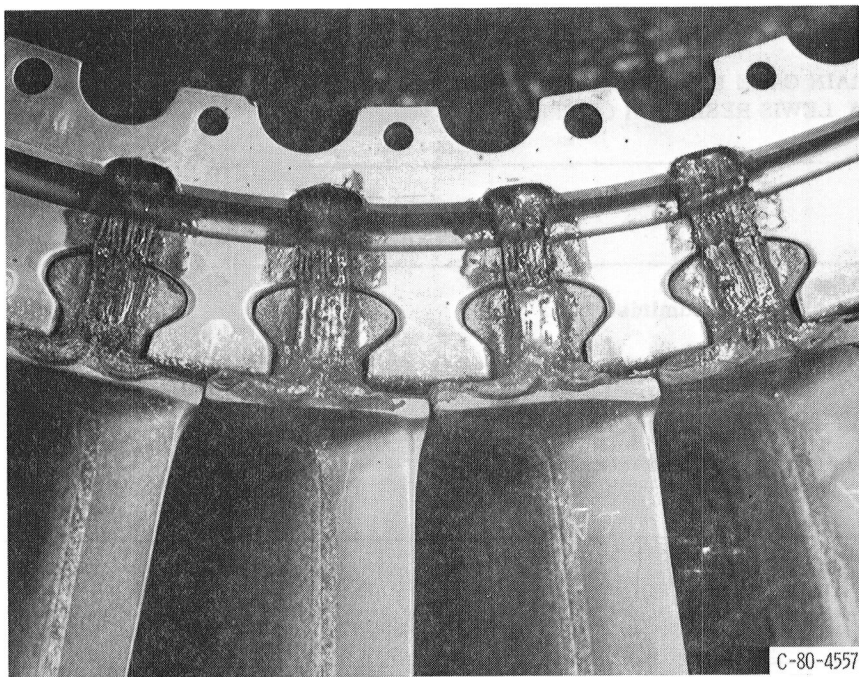


Figure 4. - Blade-to-disk jumps of strain gage systems on first stage of YF-100 engine fan.

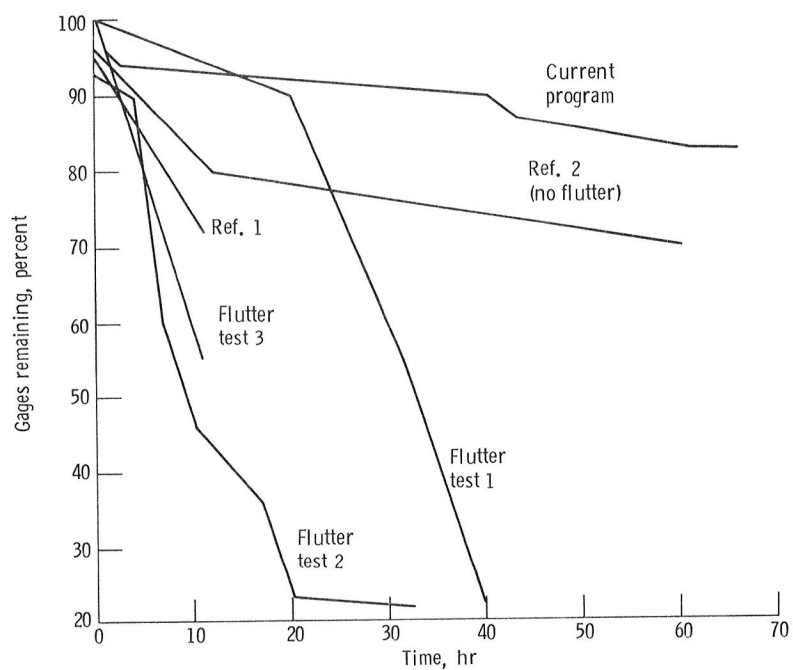


Figure 5. - Strain gage failure rates.

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